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U. S. NAVAL AIR ENGINEERING CENTER

LAKEHURST, NEW JERSEY

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METALLURGICAL ANALYSIS OF ARRESTING GEAR DECK PENDANT FAILURES

DEPARTMENT OF THE NAVY
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METALLURGICAL ANALYSIS

OF

ARRESTING GEAR DECK PENDANT FAILURES

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A metallurgical investigation was conducted to explain the nature of a failed cross-deck pendant. The pendant had completely parted during the arrestment of an F-4 Aircraft on the USS Franklin D. Roosevelt (CV-42). As part of the investigation, deck-pendants taken from tests conducted by the Naval Air Engineering Center (NAEC) at the Runway Arrested Landing Site (RALS) of the Naval Air Test Facility (NATF) were also examined. These tests were run in an attempt to simulate those conditions which might have led to the cross-deck pendant failure which occurred in the CV-42. The metallurgical studies, along

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with samples taken from cable qualifications samples supplied by NATF, gave an insight into the causes of cross-deck pendant failures. The results of the studies, along with opinions as to the cause of the CV-42 pendant failure are reported.

I. INTRODUCTION

On 26 August 1975, during the arrestment of an F-4 aircraft, an arresting cable parted; as a result, the aircraft rolled off the deck causing the loss of the aircraft, including the pilot and radar intercept officer. A complete metallurgical analysis was made of the failed cable.

In the process of the investigation, special tests aimed at simulating the conditions which led to the cable failure were conducted by the Naval Air Engineering Center (NAEC) at the Naval Air Test Facility (NATF). By examining these cables plus failed deck-pendants supplied from former wire reel qualification tests, much new information concerning various types of wire failures in deck-pendants was found.

The metallurgical investigations included 30X visual examination, metallography, microhardness and scanning electron microscopy, plus tensile and bending tests. The results of the studies, including evaluation of the cause of the FDR deck-pendant failure, are detailed in the following report.

II. SUMMARY

1. In running attempted simulation tests at the RALS site, extra attention was given to effects of less than perfect hook points. This stemmed from the fact that on the first arrestment on the FDR which followed the one in which the F-4 aircraft was lost, 11 wires were broken. Examination revealed that the hook point used in this arrestment had worn, sharp edges. The possible effects of such hook points contributing to the premature failure of the FDR cable were given special attention in the studies which followed.

2. The tests conducted by NAEC at NATF, which attempted to simulate the FDR cable failure, studied hook point quality, the amount that arrestments were off-center, and engaging speeds giving up to 115% of maximum allowable hook load as variables.

3. The metallurgical tests which led to the classification of failure modes included visual examination (up to 30X), scanning electron microscopy, metallographic examination, microhardness tests, and some mechanical test evaluation.

4. Mechanical tests on the failed FDR cable showed that the used cable still met minimum strength requirements for new wire rope. Strength of wires taken immediately adjacent to the failure showed no significant degradation of properties.

5. Metallurgical examinations of the parted FDR cable, simulation test cables and failed qualification deck-pendant test cables showed 5 basic different types of individual wire failures:

a. Wires which are severed or chopped by a sharp instrument - presumably a hook point. Such failures were found when 11 wires failed in the arrestment following the pendant failure on the FDR, and were duplicated in a simulation test at the RALS site when the same sharp edged hook point was used.

b. Wires which fail in pure tension. The tensile overloads occur when many other wires have already broken for some other reason; the tensile overload failures are then the last wires in the cable to break.

c. Shear failures - these are similar to the tensile failures above except that some cable wires will fail in shear because of heavy interstrand bearing loads found in a woven strand construction.

d. Irregular shear failures - These start as cracks in brittle surface layers which develop during previous arrestments. The cracks generate tears in the base wire. These tears allow the wire to break at reduced loads. Such failures were found to form under two sets of conditions.

1) As a result of being rubbed continously during multiple arrestments; such failures start after some arrestments have

already occurred (normally 15 - 80 for high energy arrestments). At this point, wires start to fail at a rate of one wire break per 2 - 10 arrestments; after 4 - 7 wires have failed, the failure rate increases up to as much as 3 wire breaks per arrestment. When a critical number of wires have failed (believed to be about 12 wires in a single lay length) the cable is expected to be vulnerable to a complete failure on the next arrestment.

NOTE: This is the common failure mode found in fleet service and is the basis for pendant inspection and the removal of cable after 4 broken wires are found.

2) When wire containing brittle surface layers formed in previous arrestments is subjected to a heavy tensile load which includes bending. The bend stresses can develop the same brittle cracks, initiate tears and cause wire failures similar to those described in 4D1). Under these conditions, however, many wires can fail in a single arrestment; even enough to allow failure of the remaining cable.

Such failures were found in the broken FDR cable, in failed cables taken from pendant evaluation tests and in one simulation test in which previously arrested cable was exposed to high (115% of rated hook loads) speed arrestments.

5. Fractures similar to those found in the failed FDR cables were generated in simulation tests when cable exposed to normal F-4 landing patterns were then exposed to high speed, (high load) engagements. In these tests, the high engaging speeds had to be repeated several times on the same cable before the FDR type fractures were duplicated.

6. The brittle surface layers believed to be necessary to start the cross deck pendant failures in these tests were evaluated. The coatings are those previously identified as unetched martensite. Recent work indicates the structure identification may be incorrect; the behavior as a brittle structure is the same, however.

7. The thickness of the layer formed did not vary as a result of hook point quality, excessive high speed or degree of off-center of the arrestment; the amount of surface developing the brittle layers did vary depending on conditions of the arrestment.

III. CONCLUSIONS

1. Cross-deck pendant failure modes can be determined by metallurgical analysis. At least four different causes for cross-deck pendant wire failure were found. These are:

1) Cutting of wires as a result of being hit by a sharp edged hook.

2) Repeated rubbing by hook points in a series of high energy arrestments.

3) Overload of wires previously conditioned by aircraft arrestments.

4) Even higher tensile overloads, capable of breaking wires in any condition.

2. Use of less than perfect hook points, particularly those with sharp edges, can cause severe deck-pendant cable damage.

3. The cross-deck pendant failure which occurred on the FDR was the result of a severe tensile overload during the last arrestment.

4. The fracture modes found on the failed FDR deck-pendant were duplicated in part with simulation tests performed by NAEC. These wire fractures were developed when a cable, prevously used under arrestment conditions duplicating those seen by the failed FDR cable, was exposed to overspeed arrestments.

5. The initial overspeed arrestments on the conditioned cable did not cause wire breakage. The last four high overspeed arrestments caused fracture of 17 wires, 12 of which duplicated the fractures found on the failed FDR cable.

6. Less than perfect hook points were sometimes used in the arrestments duplicating the fracture mode; however, use of these hook points without an excessive engaging speed did not cause similar damage.

7. In spite of the presence of 24 broken wires an off center overspeed arrestment did not part the test cable.

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VII. BACKGROUND

The cross-deck pendant on the FDR failed during an F-4 arrestment during night carrier qualifications. The pendant failed on the 22nd arrestment on the pendant. Aircraft weight was within prescribed limits (36,200 lb.) and at proper speeds (based on the LSO estimates). The landing occurred within the area considered "on-center". The cable parted after 85% of the arrestment was completed. Other details are covered in NAEC Misc. 09861.

Pertinent to the investigation which ensued was an incident which occurred after the pendant failure. After the accident, a new deck pendant was installed. On the first arrestment seen by the new cable, 11 broken wires were found. An examination of the hook point used in this arrestment revealed that it had been worn to a very sharp edge at the ends of the throat groove area (See figure 1). The 11 broken wires appeared to have been "chopped" or severed by the sharp hook point edge. It was then disclosed that the same hook point which had broken 11 wires in one arrestment had also been used in at least three arrestments of the cable which had failed, leading to loss of the F-4 aircraft. The possibility that the sharp edged hook point had somehow indirectly caused the ultimate failure of the cross-deck pendant was examined in some of the tests which followed.

To aid in the failure investigation, two series of test were run at the RALS site at Naval Air Test Facility, Lakehurst. A synopsis of the first tests are summarized in Table I. In these, engaging speeds were limited to those which would give maximum allowable cable tension. A second series of tests were run in which higher engaging speeds which permitted hook loads up to 115% of allowable were used.

As part of the metallurgical investigation, samples of failed deck pendants were sought for use as comparisions. Such samples were available from cable qualification test failures. In these tests, samples of all reels of cable submitted for use as cross-deck pendants are subjected to actual dead-load arrestments at conditions which create at least a 20% overload of maximum allowable cable tensions. In these tests, conducted at NATF, pendants are subjected to 20 ft. off-center arrestments using MK-7 MOD 1 gear with no sheave dampers. Samples must be capable of surviving 4 such severe arrestments before the cable material is accepted. Occasionally, either because of poor cable quality or erratic test conditions, deck pendants have failed. Several such failed samples from previous tests were available, and these fractures were used for the metallurgical investigations.

VIII. SIMULATION TEST RESULTS

Before discussing the results of the metallurgical investigations, it is helpful to review the results of the simulation tests conducted by NAEC at the Runway Arrested Landing Site (RALS) at NATF.

Here, taxi-ins of F-4 aircraft engaged test deck-pendants in a MARK 7 MOD 1 gear under conditions which attempted to duplicate the failure of the FDR pendant. The factors which were first studied were hook point quality and the degree of off-center hits. In the final test series, high speed engagements were added to the mix of "bad" conditions.

The results of these tests are summarized in Table I.

Note that in these tests, engagements were always stopped when a "critical" number of broken wires were reached, rather than because of a complete break of the cable. This is based on what is felt to be the normal pattern of deck-pendant behavior in fleet service. Here, it has been found that after some number of arrestments (which can vary greatly but normally start at about 50 arrestments for high energy engagements) single, individual wires start to break. Initially, breaks occur one every 3 - 10 arrestments. After several wires are broken, the rate of individual wires breaking increases up to a normal maximum of 3 wires/arrestment until a critical number has been reached. In previous tests conducted by NAEC, this number was 12 wires in a single lay. When such a number of broken wires were found, the cable would completely fail within the next three arrestments.

It is based on these results that deck-pendants are examined in fleet use for broken wires, and replaced when 4 broken wires are found. Such a criteria is considered conservative since it is normally well below the point at which the cable is considered capable of failing in a single engagement. That pendant failures are almost never found in fleet service (The FDR failure is the first reported in 5 years and only the 2nd such failure in 20 years) is a tribute to the safety of this failure criterion.

IX. MATERIAL AND FRACTURE ANALYSIS RESULTS

The failure analysis included mechanical strength tests of individual wires making up the failed cable (from areas where no immediate arrestment damage was noted, plus areas where rubbing and/or abrasion had occurred) plus testing of sections of the full cable.

Visual examination was made of the failed cable fracture followed by metallographic and microhardness tests of the wires making up the cable and scanning electron microscopy of the fractured ends themselves. The metallographic and microhardness tests were extended to pendants used in the NAEC simulation tests and finally to failed cables taken from cable qualification tests.

A. Visual Examination

Examination of the deck-pendant which had parted on the FDR showed that all fracture occurred over a small area. The failure was located at 47' 5" from the end of the port swaged fitting, about 3 feet off-center to starboard. Based on Plat films examined later, the failure occurred close to the point of initial impact. Some of the individual broken ends had apparently rubbed on the deck after the failure. These showed abnormal amounts of abrasion. The appearance of the balance of the cable was "normal". Some hemp extrusion was noted near the failure point, but this usually occurs in a cable after it has failed.

Two broken wires other than in the fracture area were located about 12-24 inches from the failure. These had been reported in the routine cable examination which had occurred prior to the arrestment.

Failed Wire Fracture Surfaces

The fractured ends from both sides of the failed cable were all examined individually under a binocular microscope. One observation was that on many of the wires a smooth rubbed surface was observed. This layer had been observed frequently in the past and identified as unetched or "white martensite". Subsequent tests verified the presence of this structure, although some question was raised as to the correctness of the "white martensite" identification. It is now believed that this layer of hard brittle material is similar to that found in roller bearing applications, railroad tracks and even on the inside surface of cold swaged steel terminals. As such, it is a severely deformed structure which, while similar to martensite, is even harder and does not require the time or the temperature of the wire to reach transformation temperature to develop. Tests are currently underway to verify the nature of this surface layer more accurately. For the sake of continuity in this report with previously published results, this layer will be referred to as "white martensite" for the balance of the report, even though this label may be demonstrated to be inaccurate in the future.

The classification of the wire failures are shown in Table II. While the table lists those wires containing "white martensite", closer

examination revealed that only in specific cases did the white martensite play a significant role in the fracture. Those for the port side breaks are so noted.

The fractures were of three basic types (four, if wires which show severe distortion as a result of damage after the cable fracture, are considered) These included, as the first two types, tensile cup-cone fractures and 45° shear failures, both of which are found in any severe tensile overload tests of wire rope. (see figures 2, 3). These failures are expected for the wires which break after other wires have failed first for any special reason (such as fatigue in the case of purchase cable.) As such, they are the last wires to break in typical service, but are the effects rather than the cause of the failure.

The other type of fracture noted was a jagged, irregular shear. In these failures, fracture starts on the smooth surface layer (shown later to be the martensitic-type structure). A crack forms across the brittle layer, then extends to a partial 45° shear. The back half of the wire then tends to fail in tension, (see figure four). It is the occurrance of these fractures which, it is believed, initiate the failure of the cable.

The irregular shear failures were also found when examining the fractures of the test cables which had completely broken in the pendant material qualification tests.

The fractures of the individual broken wires which were found in the RALS simulation tests were also irregular shear type. Since these are typical of fleet service broken wires, it was important to establish whether these fractures differed from those taken from the failed FDR deck-pendant. Subsequent metallographic and scanning electron microscopy examination revealed consistant differences between these apparently similar fractures. These differences are discussed in detail in this report. The significance of these differences is that it shows that the failed FDR cable fracture mode was unique for field service deck-pendants.

The 11 broken wires from the single arrestment incident were also examined. These wires were very evidently "chopped" or severed as shown in figure 5. In the simulation program conducted by NAEC at the RALS site, after the seventh arrestment using the same sharp edged hook that had severed 11 wires in a single arrestment on the FDR, 7 broken wires were found, all breaks occurring in the last arrestment. These wires had the same severe plastic deformation or chopped appearance as did the 11 wires broken in the single FDR arrestment. Thus, the damage resulting from a sharp edged hook was duplicated in the NATF tests.

Significantly, none of the wires taken from the parted FDR cable exhibited the severe local necking characteristics of the "chopped" wire failures. This indicated that while a sharp edged hook could indeed cause abnormal wire damage, this had not been a failure mode in the case of the FDR cable which had parted.

B. Metallographic Examination

Metallographic mounts revealed the presence of a second phase structure which had formed on the surface of many of the wires. The layer (which appears to be similar to unetched martensite) was found in selected areas of all the test cables examined, including those having as few as three arrestements with good hook points. Use of metal etching tests had indicated that the martensitic-type layers formed on any F-4 arrestment. Note that some degree of off center arrestment had occurred in all the tests examined.

Microhardness tests on a variety of selected wires showed the hardness of the brittle surface layers were all Rc-65-70- extremely hard, too hard for normal as-quenched martensite. The hardness was the same for all wires tested, regardless of the hook quality or number of arrestments or engaging speed used in the arrestments which created the surface layers.

Wires from pendants used in all of the RALS simulation tests were examined. In selected areas of wires from all of the cables examined, the maximum thickness of the brittle surface layers was approximately the same - about 0.003" (see figure 6). Where multiple hits had occurred, the effects of the heat of the arrestment could be seen as a tempered structure of the martensitic-type layers; however, any freshly formed unetched material still has an approximate thickness of 0.001 - 0.003 (see figure 7).

Failed Cable

The wires taken from the FDR failed cable were examined. In those wires categorized as having the jagged or irregular fractures, the presence of the martensitic-type brittle surface layer was confirmed. In these wires, the brittle surface layers contained horizontal cracks. These cracks had acted as stress raisers which then led to 45° shear tears in the base metal (see figure 8). These shear tears extended up to as much as half the diameter of the base layer. The remaining reduced cross section of the wire then failed in tension.

The preponderence of the irregular jagged fractures were found in three adjacent strands. It is believed that failure first occurred in these strands. In the opposite strands the wires exhibited mostly tensile and shear fractures. When martensitic-type surface layers were present in these strands, any perpendicular crack appeared to stop as it extended into the base metal. The cracks would tend to "blunt out" as they entered the base metal. (See figure 9).

General Surface Cracks

In examining wires taken from the RALS simulation tests, it was found that two different types of cracks developed in the brittle martensitic-type surface layers. The straight cracks which were similar to those observed in the FDR cable were found in cable having had 7 arrestments

with a "bad" hook point; with 5 - 7 arrestments made with a "new" hook point, cracks found in samples taken from the RALS tests show a curved crack. (Figure 10).

It is believed that the "straight" cracks, completely perpendicular to the rubbed surface are a result of bending in wire which contains previously formed martensitic-type brittle surfaces. The "curved" cracks are thought to be the result of severe rubbing of a previously formed brittle layer, and is more like a spalling crack. Both types require previously formed brittle surface layers, but then result from different types of applied stress.

Cable exposed to 22 arrestments with a "good" hook point exhibited both straight and curved cracks (See figure 11). It can not be stated whether or not the earlier appearance of the straight horizontal cracks were a result of the use of the sharp edged hook point, or merely the result of material containing martensitic-type surface layers having been bent in tension earlier in this one cable than in others. Note that in the single arrestment in which the sharp edged hook broke 11 wires, a heavy martensitic-type layer was found, but no cracks were observed (See figure 12).

Here, one of the two major significant differences between the FDR failed cables and the individual broken wires from the simulation tests were observed. Except for the fractured wires in the last test cable (discussed later) all the individual broken wires in the simulated RALS tests showed the curved type cracks in the martensitic-like layers (See figure 13).

In the last simulation test, a deck-pendant exposed to arrestments which simulated those seen by the cable which ultimately failed on the FDR was then exposed to a series of high speed engagements using a variety of hook points. For the first time in the simulation tests, fractures were observed which were similar to those found on the FDR. The wires whose fractures duplicated those found in the failed FDR cable were found on the side opposite from where the cable had been rubbed. Those fractured wires taken from the area in which the hook had obviously been rubbing most frequently exhibited fractures typical of those taken from cables in which normal slow, individual wire failures occur. (See figure 14).

C. Mechanical Property Tests

An eight foot section of deck-pendant taken away from the fracture area was cut from the failed FDR cable. After pouring sockets on both ends, the cable was pulled to destruction. The cable broke at 193,000 lb. This value, while it showed some drop-off from the original cable reel values (200,000 lb.) still exceeded the minimum requirements for cross-deck pendant cable of 188,000 lbs.

Individual wires were also pulled so as to determine strength of wires near the fracture itself. The results are shown in Tables II and IV. Because of the distortion of the wires taken from the area near

the fracture, it was difficult to measure reductions in area. It can be seen however, that the wires from the FDR cable are normal for this type of pendant and show no drop-off in strength.

Several wires of one strand did break at lower than normal tensile values. Examination revealed that these wires might have seen bending through martensitic-type surface layers.

To establish that bending through brittle layers could allow low break failures, wires were exposed to impact bend loads using a Gardner impact adherence test (See appendix for description). Here it was found that wires containing martensitic layers would break at much lower values if they are hit so that the brittle layer is bent in tension. With no martensitic-type layer, or with the brittle layer bent in compression, the wires could not be broken in these tests.

A series of wires taken from various RALS tests were then tested, all such that the wires were impacted with the brittle martensitic-type surface layers in bending tension. Results in Table IV show that with one unexplained exception, all wires, including those taken from the FDR failure, rapidly reach a constant low breaking value.

D. Scanning Electron Microscope

The fractured surfaces of the failed deck-pendants wires were examined with a scanning electron microscope at the Franklin Institute Research Lab and at the Naval Air Rework Facility (NARF) at North Island and at Jacksonville.

Except for the initiating cracks found in the brittle martensitic-type layers, all the fractures were ductile (void coalescence) type tensile breaks.

The fractures of the failed FDR cable wires, believed to be the first to fracture, originate with a brittle crack through the martensitic-type layer. These fractures show a fine celled structure with almost no ductility. The crack then becomes a ductile shear tear as it extends into the base wire. Finally a second ductile tear results from where the 45^{o} shear tear stops. (See figures 15, 16).

As opposed to this type of failure, a typical fracture of an individual wire which fails as a single break in the course of normal arresting cable life is shown in Figures 17 thru 20. The crack through the martensitic-type layer is frequently layered. This results from the fact that the brittle layer always shows indication of multiple hits in this area with resultant partially tempered layers. As the crack starts through the tempered layer (or possibly starts at the interface of a tempered- non-tempered layer) its propagation path alters.

In addition to the layering effect through the brittle zone, all of these single wire failures show evidence of at least two separate crack initiation sites. In Figure 17 the presence of smeared metal leading to a second crack direction is seen over the straight crack, showing that metal was deformed and a second crack started after the

first brittle crack had formed. The ductile tear portion, when viewed by the scanning electron microscope at first gives the appearance of a fatigue surface. Closer examination at higher magnification reveals this is actually a "rubbed" structure. This, however, does show that the ductile tear is present for more than one arrestment (See figures 19, 20).

X. DISCUSSION OF RESULTS

Before discussing the significance of the metallurgical examinations, some comments are necessary about general observations made during the NATF simulation tests. Micro etch tests showed that the brittle martensitic-type layers appeared after the first off-center F-4 arrestment. The amount formed would vary with the amount of stick-slip involved, so that the more off-center the arrestment, the greater the quantity of brittle surface layer formed. (Stick-slip is the phenomenon in which, during an off-center arrestment, a hook point cold welds to the cable until a break-away force builds up, forcing the hook to slide rapidly along the cable.) It also appeared that for all other conditions being the same, the amount of "martensite" layer formed in a given arrestment increases if a sharp edge hook point is used.

The brittle layer forms only where the cable is rubbed by the hook point. Because the cable is twisting, however, the entire periphery of the surface may be covered after a certain number of arrestments. At times the cables had 360° coverage of brittle surface layer in some areas after 7 arrestments. It was observed that at some point, the cable takes an oval shape. Once this happens, the path of the hook starts to follow a set pattern. Transverse cracks in the brittle surface layer start to appear after the second or third arrestment. The type and amount of these cracks can not be accurately determined in these tests. It is believed that the straight transverse cracks shown in Figure 21 result primarily when a previously formed layer is bent in tension.

The metallurgical investigations showed several significant things.

1. Wires broken as a result of chopping action by sharp edged hook point have characteristic severe local deformation just below the fracture. These were not present in the fractures taken from the FDR cable failure.

2. The typical failure cycle of deck-pendant cables in which individual wires fail over the course of several arrestments leads to a fracture mode of the individual wires which while not fatigue failure in the classical sense, do demonstrate dependance on more than one arrestment prior to fracture. None of the failed wires taken from the parted FDR cable showed this type of fracture.

3. At least 16 of the wire fractures from the failed cable have brittle fracture initiation through a thin martensitic-type of brittle surface layer. This brittle surface layer in the presence of a bending action would allow the wire to break under a reduced tensile load.

4. In other arrested cable, including many supplied by the tests conducted at NATF, it was found that the brittle martensitic type layers are present after any off-center F-4 arrestment. The maximum thickness of the layer does not seem to be dependant on the number of arrestments or on the quality of the hook point. The structure of this layer appears to be the same also (based on microhardness readings) although x-ray diffraction analysis is required to verify this.

5. Fractures similar to those found in the failed FDR cables were generated in simulation tests when cable exposed to normal F-4 landing patterns were then exposed to high speed (high load) engagements.

The significance of the different fracture modes identified deals with the question of how much prior damage might have existed prior to arrestment in which the FDR deck-pendant failed. Since it has been known that pendant wires may develop cracks, and that normally individual wires break over a number of arrestments, the question arises of how much wire damage might have existed prior to the arrestment which parted the cable.

Of the wires from the FDR failed pendant which did not break as tensile or shear breaks, a jagged, irregular shear was noted. These fractures are similar to those which develop slowly over a period of arrestments in normal cable life. Such fractures could have started prior to the last arrestments, the last hit serving only to finish the fracture. The difference in the fracture mode identified indicates that such was NOT the case. The fracture mode found in the FDR cables appears to be different from those normally found. It is a fracture in which cracks initiate and progress to the point of failure as a result of a single overload. Thus, while preconditioning to the extent that brittle surface layers had to have formed in an area where overload and/or bending can cause fracture, the fracture itself occurs completely during the final arrestment!

In the examination of the failed cable, emphasis is placed on the fractures of wires containing the brittle martensitic-type surface layers. It should be noted that deck-pendants can fail without such surface layers if exposed to a sufficiently high tensile load. One such failure has occurred in the cable qualification tests in which a cable failed on the first dead load test.

In that cable, no martensitic type brittle layers had caused fracture. All wires showed tensile or shear fracture. Very severe notching was observed (See figure 22). As opposed to the deformation on "chopped" or cut wire failures, these notches were longitudinal indents. The general impression was that the wires had been pushed severely, causing them to press abnormally against each other until the cable parted from the overload.

In other failures which occurred after 2 or 3 prior arrestments, some martensitic-type shear induced fractures were found which were similar to those in the failed FDR cable (See figure 23).

These tests showed that if the overload is great enough, cable can fail without the presence of the brittle surface layer; however, in the only known case in which this did occur, the individual wires showed severe notching. This notching was not observed in the FDR cable failure.

Tests at Track 1 at NATF have shown that when only one or two full strands fracture, it is the wire not being rubbed by the hook point (material in maximum bending tension) that will fail first. Since the lowered breaking strength of these wires is a result of having brittle surface layers being bent, then obviously the presence at such materal will

allow failure to occur at reduced cable loads.

Since the brittle surface layers are always present, their presence alone is insufficient to cause cable failure. While the studies discussed have shown that premature damage to the wires which failed did not occur, close examination of the RALS test in which FDR fracture modes were finally duplicated suggests one other possibility. Examination of table VI in which the history of a test cable is summarized shows that damaged wires started to occur rapidly only after several excessively high speed arrestments had first taken place with no apparent wire damage. It is possible that these arrestments had weakened the general cable strength through variables like core damage such that the energy of the later excess speed arrestments was able to finally transmit loads which caused damage to the wire opposite the hook rub area. Of course, if the speed and/or energy of the arrestment which finally caused failure had been great enough, such cable weakening would not have been necessary.

Hook Point

The possibility of a sharp edged hook having caused preliminary breaks through a cutting action has, if anything, been discounted in the NATF tests; however, the possibility of a hook somehow grabbing the cable to cause a greater than normal peak load was considered as a possibility.

In this area of discussion, the hook which was on the aircraft which parted the cable was retrieved from the aircraft and examined. The hook (S/N 11553) had disturbed metal along the toe just below the throat area. (See figures 24, 25). At first it was believed that the damaged area resulted from impacting some deck structure after the deck-pendant had failed and the aircraft was going off the carrier. Closer examination revealed some wire marks in the disturbed area had formed prior to an arrestment. Some grease was found below the spalled areas which was found to contain charred hydrocarbons, indicating the hook had been exposed to a jet blast after the disturbance had occurred- again indicating the disturbed metal was present prior to the last arrestment. Since the time of the FDR cable failure, a hook point was found at NAS Oceana which presumably had had only one bolter. The damage to this hook (See figure 26) is similar to that taken off of the aircraft which had parted the cable except that the damage is even more severe.

The use of this same hook point (S/N 11553) was not, in itself sufficient to duplicate the FDR failure in the simulation tests. This hook was used in some of the tests on the cable in which the FDR fracture mode was partially duplicated. Its effect could have been significant in duplicating the fractured wires which resembled those found in the FDR; however, close examination of the records show that four of the high speed engagements caused multiple wire failures. These engagements had used three different hook points including S/N 11553 and all three caused the same amount of damage. (See Table VI).

Again, even if a disturbed hook had caused or contributed to the failure of the wires which initiated failure, the results of the RALS

tests did show that higher than normal cable tension loads are still required before the remaining cable will fracture.

Cable Quality

The tests have indicated that individual "wires" had not started to to fail before the final arrestments. The RALS simulation tests did show that overall cable quality might deteriorate as a result of prior arrestments. In such a case deterioration would be related to core quality, rather than wire strength.

Table VI did show that high speed arrestments did cause a duplication of the FDR type fractures but only after several high speed engagements had been completed with no severe obvious damage. Since the highest load used was still unable to break the test cable, it is reasonable to assume that the cable loads created in these high speed engagments were still below that needed to cause a complete failure. Initiation of the FDR type fractures may have required some local overload which resulted only after some wires broke as a result of normal wire fatigue. Then the cable stresses imparted by the high speeds used would increase as a result of these local overloads which could have initiated the FDR type failures. The other possibility is that loads increased as a result of hemp deterioration. Such deterioration is reflected in the oval shape taken on by the wire after a number of arrestments. This could allow more of the engaging load to be taken by the wires opposite the hook point. Since these wires are the ones which duplicate the FDR breaks, any mechanism which puts heavier loads or greater bending on these wires accelerates failure.

Finally, whether the premature wire fractures came from deteriorated cores, severe bending as a result of bad hook points or even severed wires, the fact that a preconditioned cable could survive a high speed, high load engagement with 24 broken wires indicates that the load which completely failed the FDR cable had to be even higher than that created by a 125 MPH engaging velocity.

XI. TABLES

TABLE I

SUMMATION OF SIMULATION TESTS

Pendant s/n	Hook Point	Arrestments	Velocity Range & MPH	Amount Arrestments Off Center: Ft. Off Center	%	Reason for Test Stoppage
BB41213-H	Good	3	90-101.5	6	100	Examination of Deck Pendant
BB41210-H	Good	7	105.0-119.0	6	100	Examination of Deck Pendant
BB41211-H	Sharp Edged	7	112.0-118	9+	100	12 Broken wires on Last Arrestment.
BB41212-H	Sharp Edged	5	117.0-121.0	7+	100	7 Broken wires all on last Arrestment
DR37905-H	Good	22	112-117.0	9+	100	5 Broken wires
BB41217-H	Good	26	113.4-116.5	8+	100	7 Broken wires
DR-37806-H	Good	43	111.0-119.0	On Center 7+	80 20	7 Broken wires (culm)
BB-41216-H	Good	83 (3HP's used)	111.0-118.6	On Center 7+	80 20	9 Broken wires
BB-4100-H	New	9	121.0-124.5	8+	100	10 Broken wires
BB-41111-H	Sharp Edged	12	119.4-125.2	8+	100	15 Broken wires
BB-41112-H	Bad Coating in Throat	19	118.0-124.3	8+	100	Examination of Deck Pendant Only 1 BW
DR-37870-H	Good	22	111.0-125.1	8+ 2.5	85 15	24 Overall Broken wires
	Bad and Good Hook Points Mixed	21		6-7 3-5	50 50	6 on Last Arrestment

TABLE II

INDIVIDUAL WIRE FRACTURE CLASSIFICATION FOR FDR FAILED CABLE

STARBOARD SIDE

STRAND	TENSILE	SHEAR	PINCHED	IRREGULAR SHEAR	WIRES WITH BRITTLE SURFACE LAYERS (UN-ETCHED MARTENSITE)
#1	4	8	------	2	4
#2	2	8	2	4	5
#3	3	9	-------	8	9
#4	5	5	2	4	6
#5	1	8	3	3	3
#6	7	3	2	2	4
TOTAL	22	42	9	19	31

TABLE III

TENSILE STRENGTHS OF FDR CABLE WIRE TAKEN NEAR SWAGED TERMINAL

STRAND # 4

OUTER LAYER	TENSILE STRENGTH, PSI	% REDUCTION IN AREA
#1	303,245	41.0
2	294,990	38.5
3	302,385	43.0
4	317,680	43.5
5	303,245	43.0
6	303,865	43.5
7	303,865	39.0
8	314,915	42.0
9	311,230	38.0
10	317,680	40.0
11	308,525	42.0
12	294,430	41.5
INNER LAYER		
1	315,020	
2	307,640	
3	296,820	
4	307,690	
5	296,820	
6	307,690	
7	307,690	
8	303,920	
9	303,920	
10	315,020	
11	303,920	
12	307,960	

TABLE IV

MECHANICAL PROPERTIES OF THE WIRE MAKING UP
THE FAILED FDR CABLE TAKEN ADJACENT TO THE FAILED AREA

OUTER LAYER WIRE AND STRAND #3	TENSILE STRENGTH PSI	PERCENT REDUCTION OF AREA
1	291,600	44%
2	282,600	Area Flattened
3	277,100	Reduction in
4	306,000	Area Measurements
5	280,000	Could not be
6	316,050	Made
7	282,600	"
8	282,600	"
9	285,250	"
10	275,000	"
11	302,700	"
12	291,600	"
STRAND #4		
1	281,780	"
2	292,600	"
3	276,500	"
4	283,600	"
5	297,420	"
6	302,600	"
7	292,130	"
8	278,950	"
9	282,600	"
10	230,850	"
11	249,500	"
12	250,800	"

TABLE V

IMPACT TEST RESULTS FOR WIRES TAKEN FROM VARIOUS CABLES

CABLE FROM WHICH WIRE WAS TAKEN (NO. ARRESTMENT, HOOK QUALITY)	SURFACE CONDITION	MINIMUM IMPACT LOAD TO FAILURE (in. - lbs.)
For Failed Cable	"Martensite" Layer Bent in Tension	70
For Failed Cable	"Martensite" Layer Bent in Tension	60
For Failed Cable	"Martensite" Layer Bent in Compression	> 160
3 Arrestments, Good Hook Point	"Martensite" Layer Bent in Tension	80
3 Arrestments, Sharp Edged Hook Point	"Martensite" Layer Bent in Tension	80
7 Arrestments, Bad Hook Point	"Martensite" Layer Bent in Tension	65
22 Arrestments, Good Hook Point	"Martensite" Layer Bent in Tension	60
26 Arrestments, Good Hook Point	"Martensite" Layer Bent in Tension	60
43 Arrestments, Good Hook Point	"Martensite" Layer Bent in Tension	60
22 Arrestments, wires taken from area not impacted by Hook Point	No Surface Layer	> 160

TABLE VI

DECK PENDANT TEST DATA ON SIMULATED FDR CONDITIONS
PLUS OVERSPEED ARRESTMENTS

PENDANT #DR37870-H

ARRESTMENTS ON PENDANT	VEL.	AIRCRAFT WGT.	G'S	HOOK	FEET OFF CENTER STBD (FT.)	% OVERLOAD	# BROKEN WIRES	TOTAL #BW
1	112.9	36.3K	3.14	9898	4			
2	111.3	37.7K	3.24	"	4			
3	117.2	37.2K	3.48	"	4			
4	109.1	36.4K	2.94	12118	3			
5	117.3	36.5K	3.38	"	4			
6	121.5	37.7K	3.70	"	4	6.0		
7	117.9	37.4K	3.77	"	8	5.0		
8	107.8	37.7K	2.94	"	5			
9	112.2	37.4K	3.15	"	4			
10	123.4	37.0K	3.88	"	4	9.3		
11	117.7	37.5K	3.62	11108	2			
12	122.6	37.0K	3.95	"	3	8.5		
13	114.4	36.6K	3.45	"	5			
14	113.9	36.2K	3.48	"	5			
15	108.3	37.7K	3.10	7441	8			
16	119.5	37.4K	3.56	"	4	5.4	1 BW	1
17	118.8	37.0K	3.75	"	13	8.9		"
18	114.5	37.5K	3.39	9898	4			"
19	114.2	37.2K	3.41	"	4			"
20	117.8	36.7K	3.77	"	4	2.0		"
21	118.7	37.5K	3.58	11553	5	5.0		"
22	123.2	37.5K	4.04	7441	5	9.4		"
23	120.2	37.2K1	3.92	"	4	6.6		"
24	118.6	37.4K	3.68	9898	5	1.5		"
25	122.4	"	4.02	"	5	11.6		"
26	117.6	"	3.69	11553	6	9.4	1 BW	2
27	122.5	"	4.00	"	6	6.6	1 BW	3
28	123.0	"	5.04	7441	5	1.5		"
29	116.4	"	4.10	"	4	11.6		"
30	121.8	"	3.50	9898	3	4.6		"
31	121.8	"	3.80	9898	3	8.6		"
32	122.5	"	4.04	11557	6	8.0		"
33	125.0	"	4.25	"	6	12.1		"
34	120.3	"	3.75	7441	6	7.5		"
35	121.9	"	3.88	"	4	11.8	1 BW	4
36	118.7	"	3.72	9898	6	2.1		"
37	125.1	"	4.21	"	6	11.4		"
38	121.9	"	3.78	11553	6	11.9	1 BW	5
39	122.8	"	3.91	"	6	13.4	4 BW	9
40	121.8	"	3.94	7441	3	7.6	4 BW	13
41	123.3	"	4.15	"	4	10.7	3 BW	16
42	117.9	"	3.75	9898	4	2.9		"
43	122.6	"	4.11	"	7	8.4	6 BW	22

TABLE VI (CON'D)

HOOK POINT DATA FOR ABOVE TEST

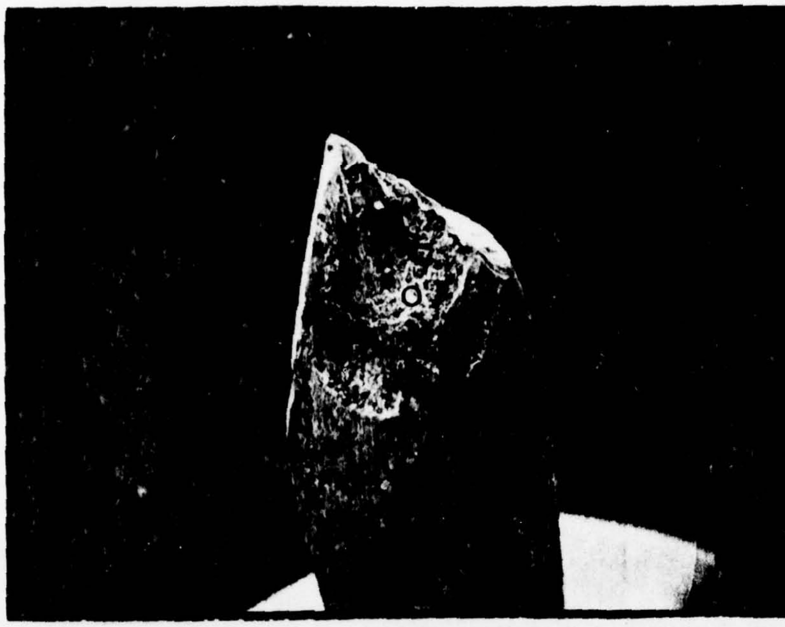
(PENDANT #DR37870-H)

HOOK POINT SERIAL #	OVERALL CONDITION	HEEL CHIPS	THROAT CHIPPED	BOTTOM ABRATION	TOE SHARPNESS	THROAT SPALLED
12118	N E W--					
7441	N E W--					
10668	USED	YES	SLIGHT	POOR	POOR	SOME
9898	GOOD USED	NO	------	OK	OK	NO
11108	BAD	NO	------	POOR	SEVERE	SOME
11553	BAD	NO	YES	SEVERE	SEVERE	YES

XII. FIGURES

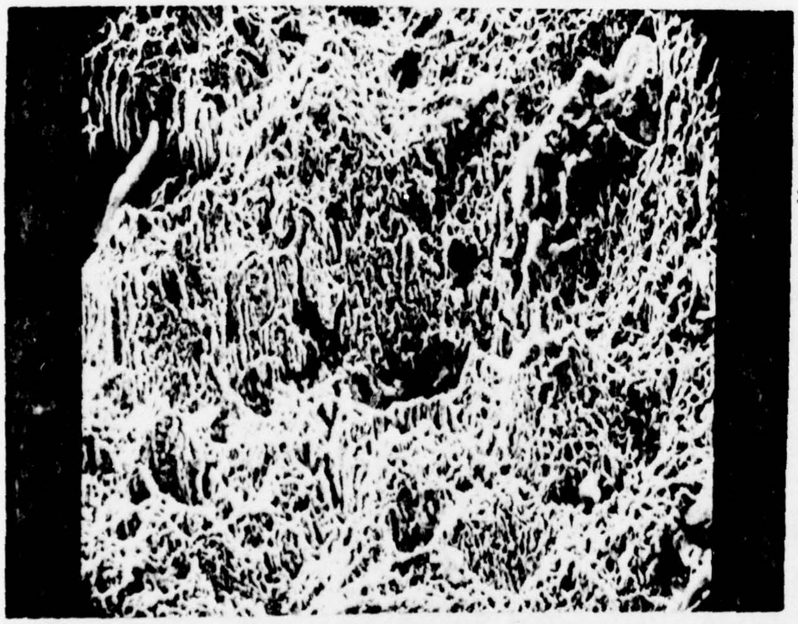
FIGURE 1

Side View of the Edge of the Hook Point which Damaged A FDR Cross Deck Pendant (11 Broken wires) in a single Arrestment.



(20x)

SEM photograph of tensile fracture. Area contained within "O" is shown below.



(800x)

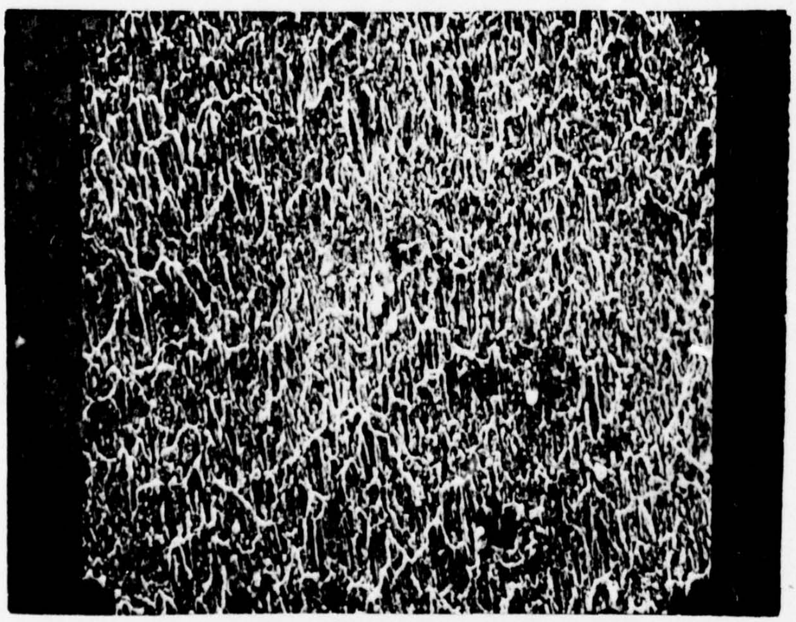
SEM photograph of transgranular fracture indicative of an overload failure.

FIGURE 2

Typical Tensile Fracture

(20x)

SEM photograph of 45^{o} shear fracture. The area contained in "O" is shown below.



(800x)

SEM photograph of transgranular fracture resulting from an overload failure.

FIGURE 3

Typical Shear Fracture

(2x)

FIGURE 4

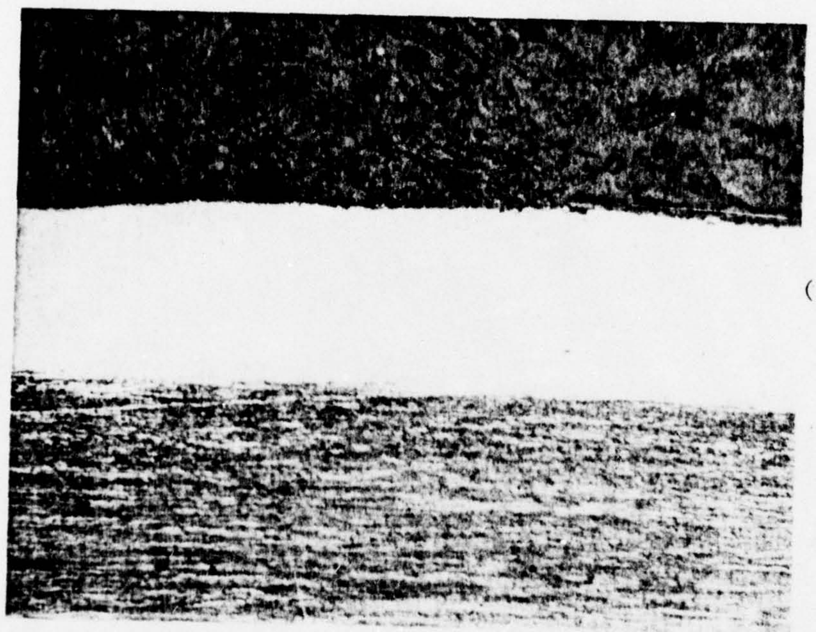
Samples from FDR failed cable showing heavy martensite layers and cracks.

(2x)

NOTE severe wire deformation

FIGURE 5

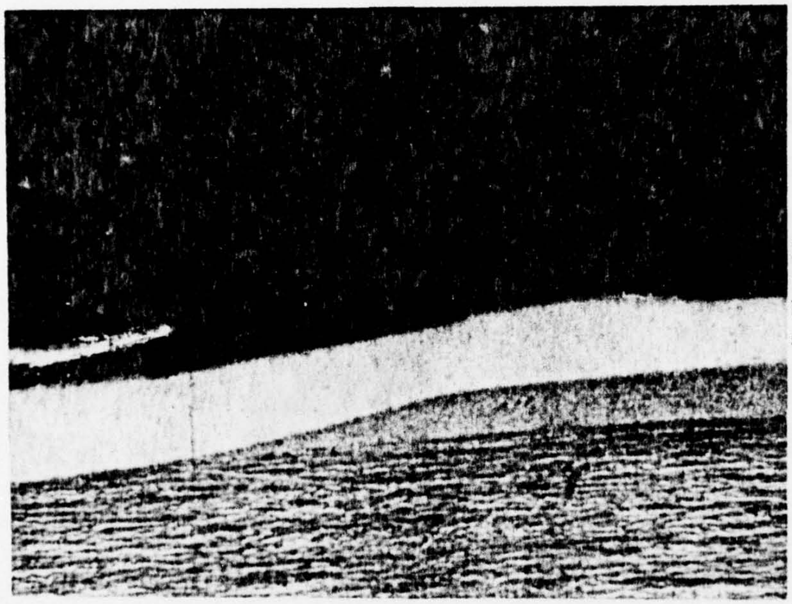
Sample wires from FDR cross deck pendant which sustained heavy damage (11 Brokenwires) in a single arrestment.



(200x)

FIGURE 6

Typical layer of "white martensite"

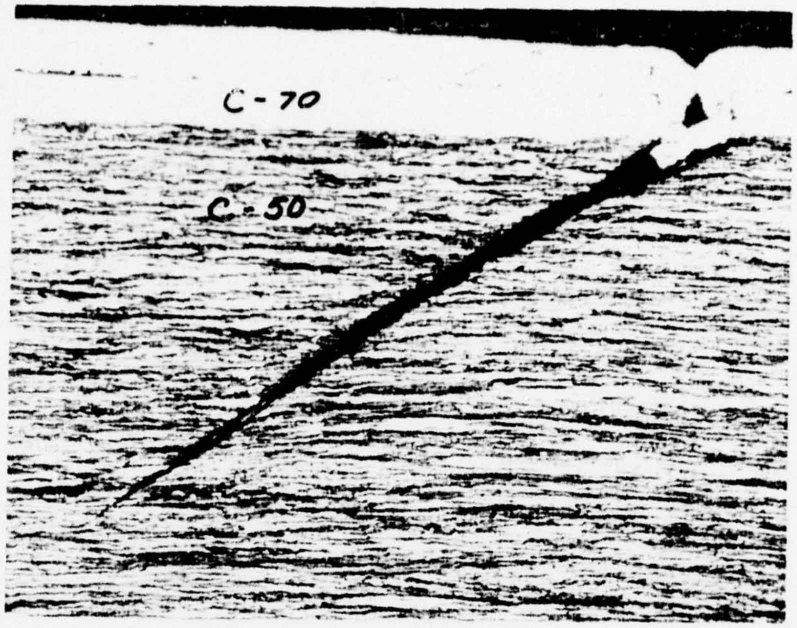


(200x)

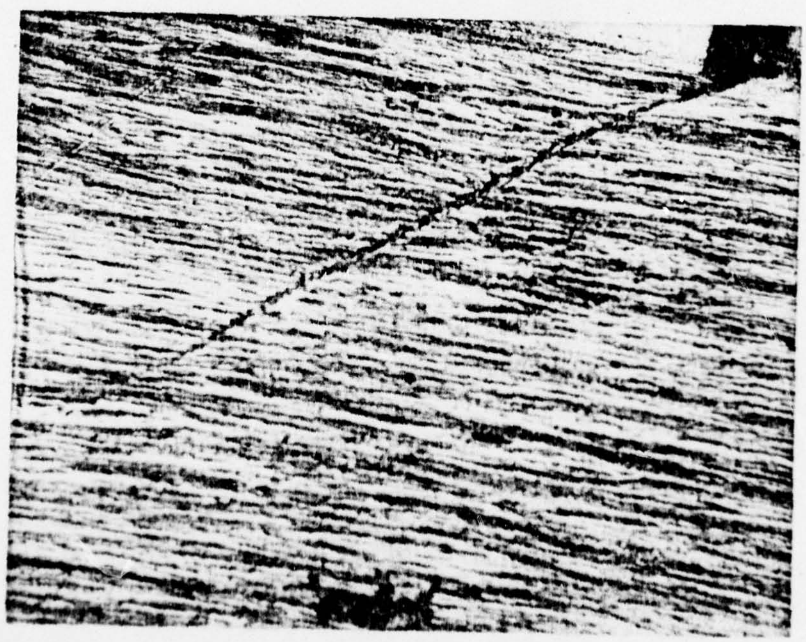
NOTE that maximum thickness has not been changed by second arrestment

FIGURE 7

Details of a multiple hit wire sample showing a freshly formed layer of "white martensite" on top of a tempered layer.



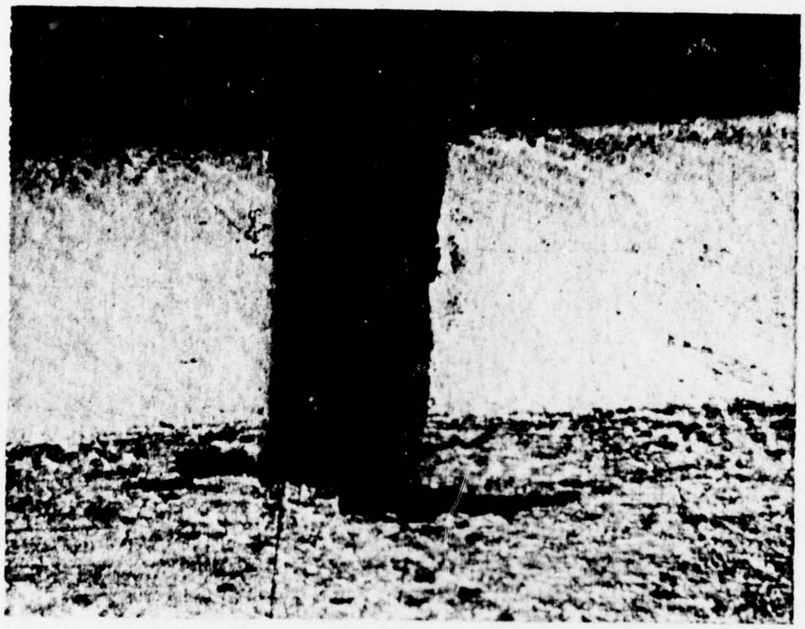
(200x)



(200x)

FIGURE 8

Details of martensite crack and resultant 45° shear in 2 FDR failed cable samples.



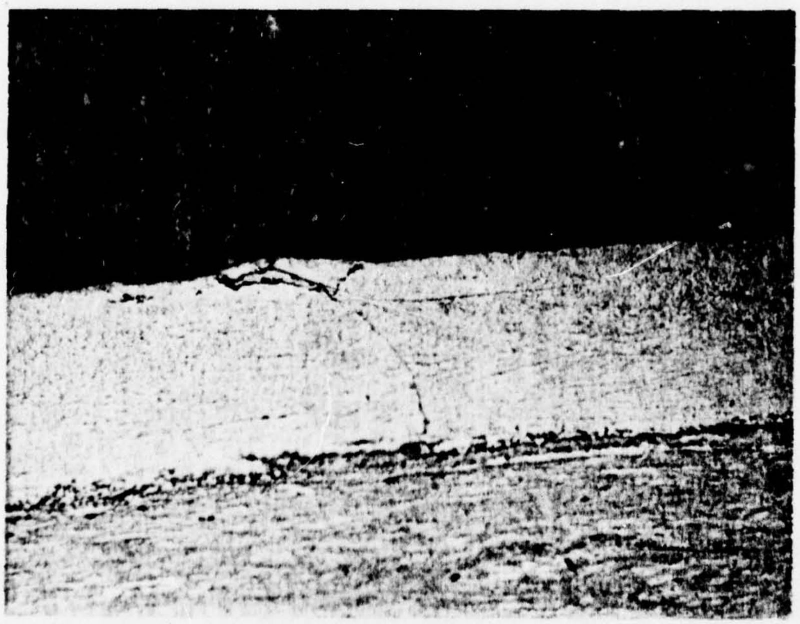
(400X)

NOTE how crack propagation stops after slightly penetrating base metal

FIGURE 9

Details of a Blunted Crack

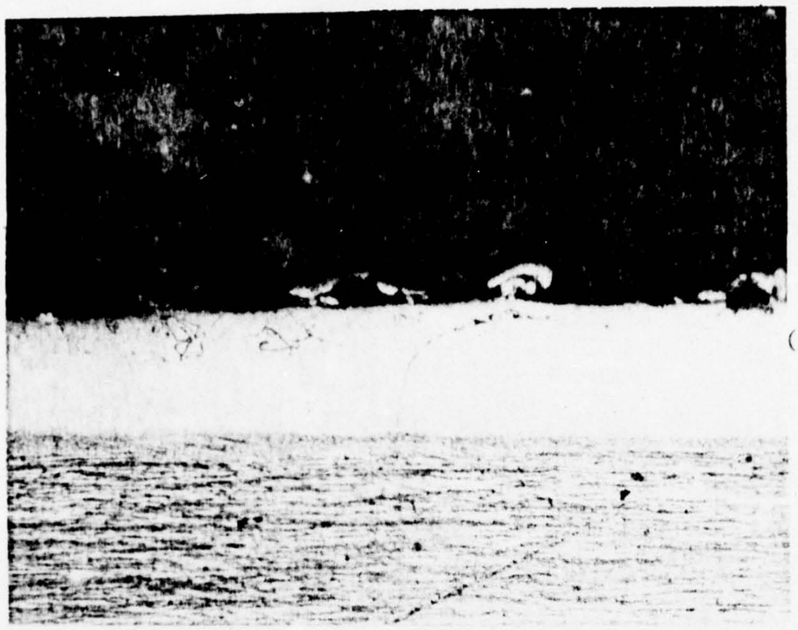
(500x)



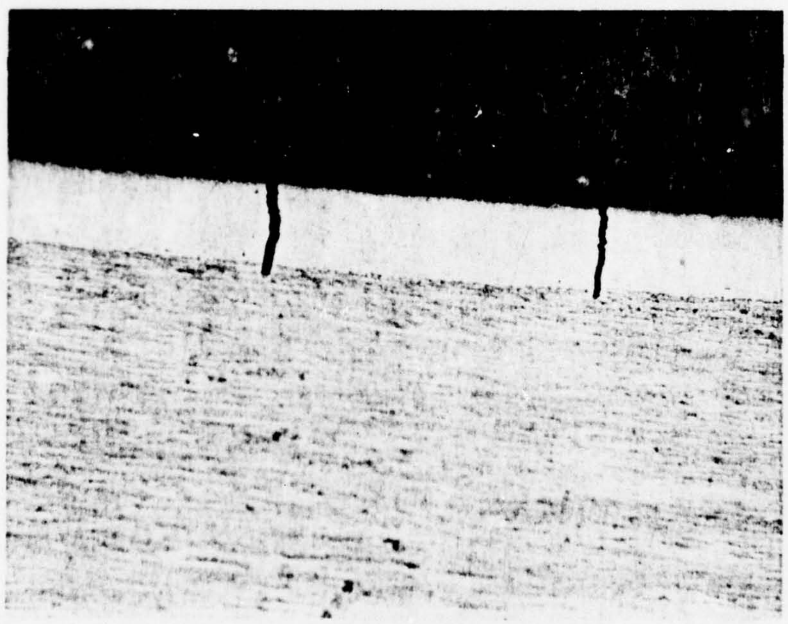
(500x)

FIGURE 10

Details of the spalling type crack found in NATF (RALS Site) wire specimens.



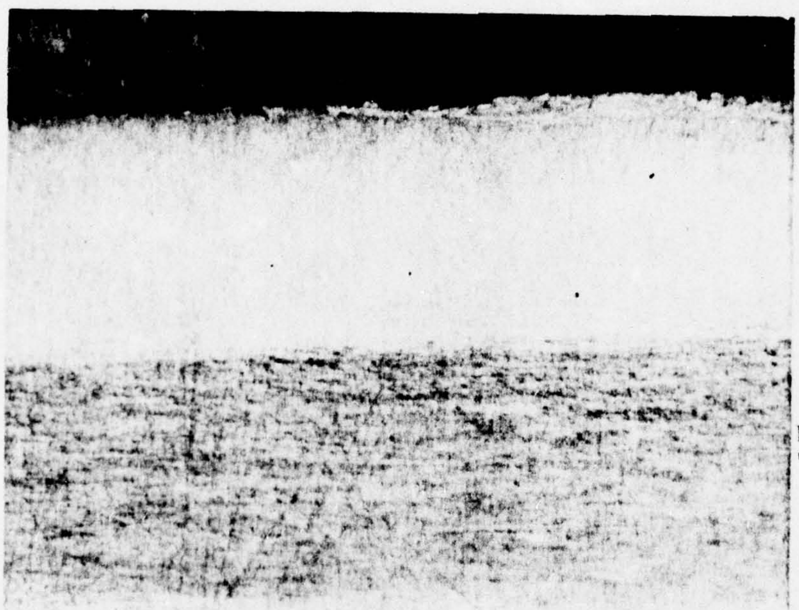
(200x)



(200x)

FIGURE 11

Details of both straight and curved type cracks found in RALS test cable with 22 hits and good hookpoint.



(400x)

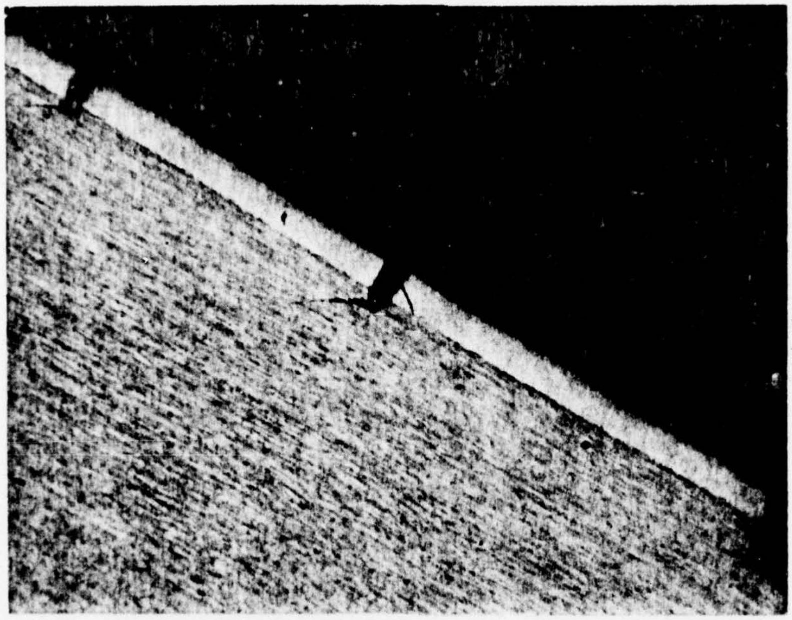
NOTE thickness of "martensite" layer.

FIGURE 12

Details of wire sample from the FDR cable with only one arrestment which sustained heavy damage (11 broken wires)

FIGURE 13

Typical spalling crack found in NATF (RALS Site) test cables.



(50x)

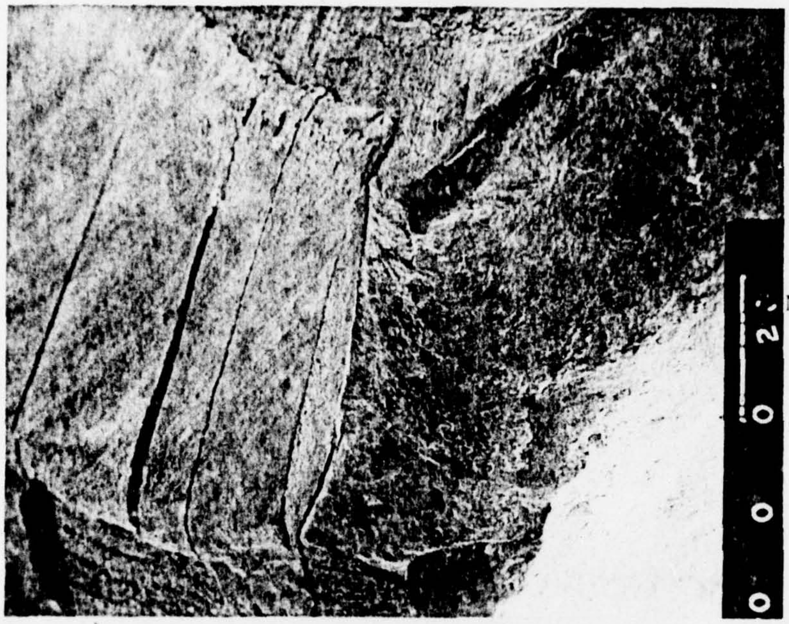
Wires opposite direct hook slide.

(50x)

Wires rubbed directly by hook point.

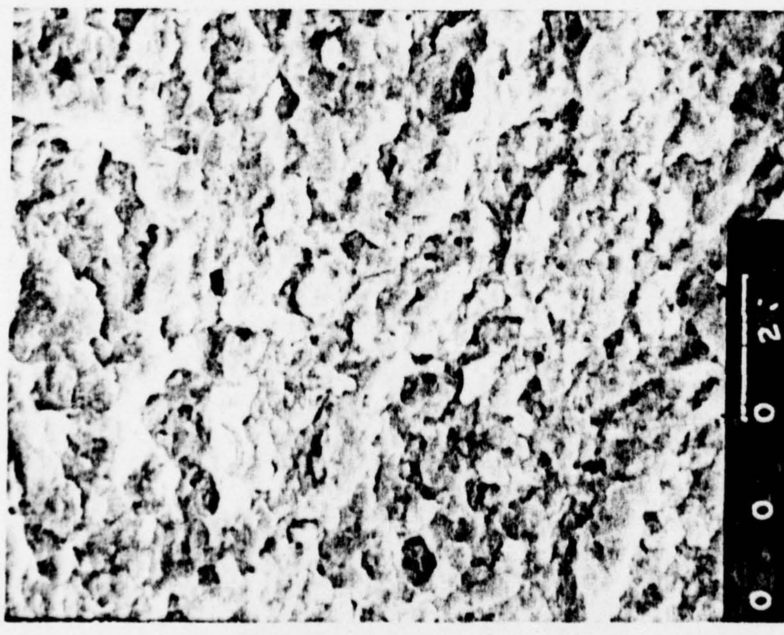
FIGURE 14

Cracks formed in wires rubbed by hook point vs. cracks in wires opposite hook slide.



(50x)

NOTE Transverse cracks



(3000x)

NOTE Fine celled structure

FIGURE 15

Details of cracks in "martensite" layer

(300x)

NOTE Martensite layer at top and center, and ductile shearing below.

FIGURE 16

"White martensite" induced fracture.

(50x)

NOTE smear at upper right hand corner

FIGURE 17

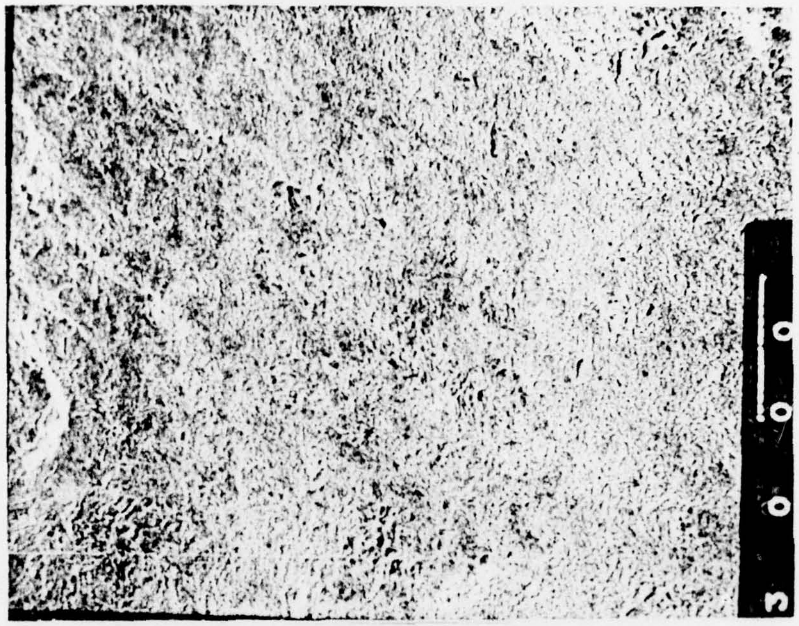
Typical individual wire fracture (type which occurs at a rate of one or two per arrestment).

(300x)

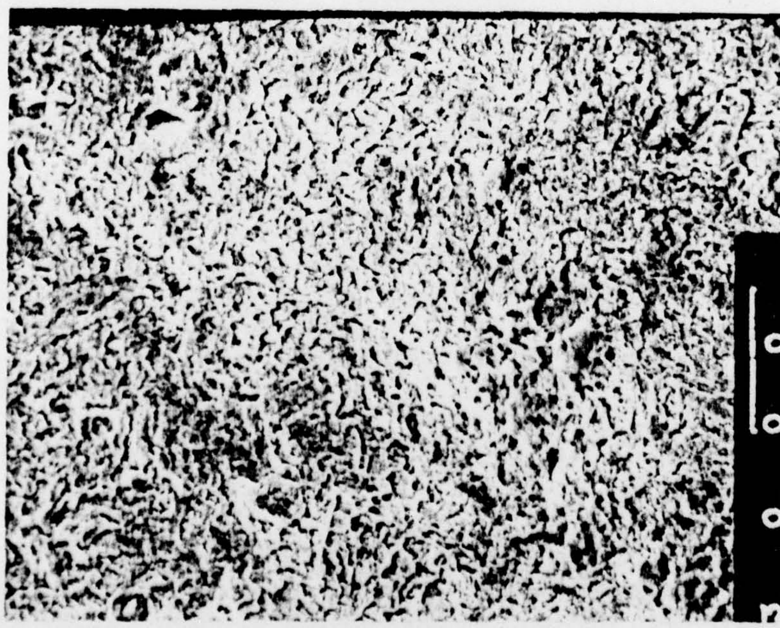
NOTE double layer of "white martensite" caused by additional hook abrasion

FIGURE 18

Enlargement of Figure 17



(300x)



(1000x)

FIGURE 19

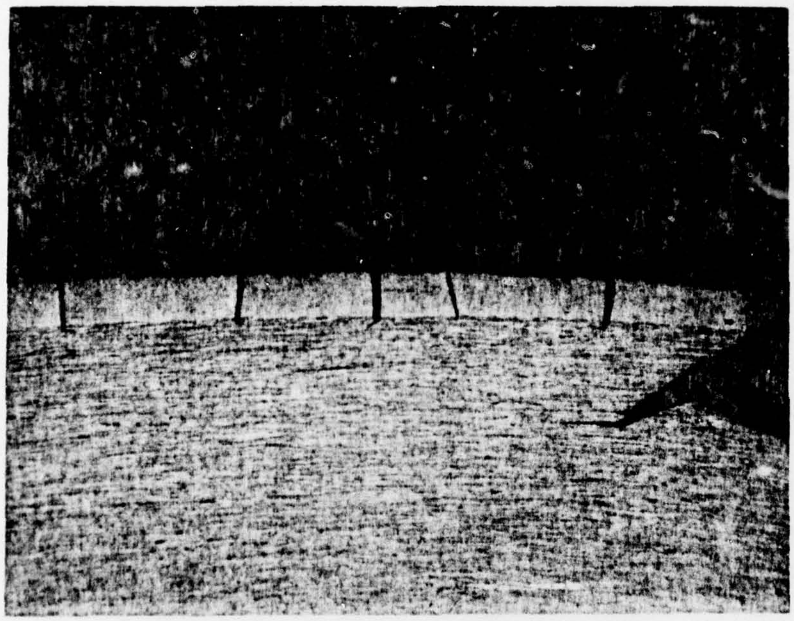
Individual wire fracture illustrating apparent fatigue structure.

(3000x)

NOTE that higher magnification reveals fatigue appearing structure is actually ductile.

FIGURE 20

Same as Figure 19 except at higher magnification.

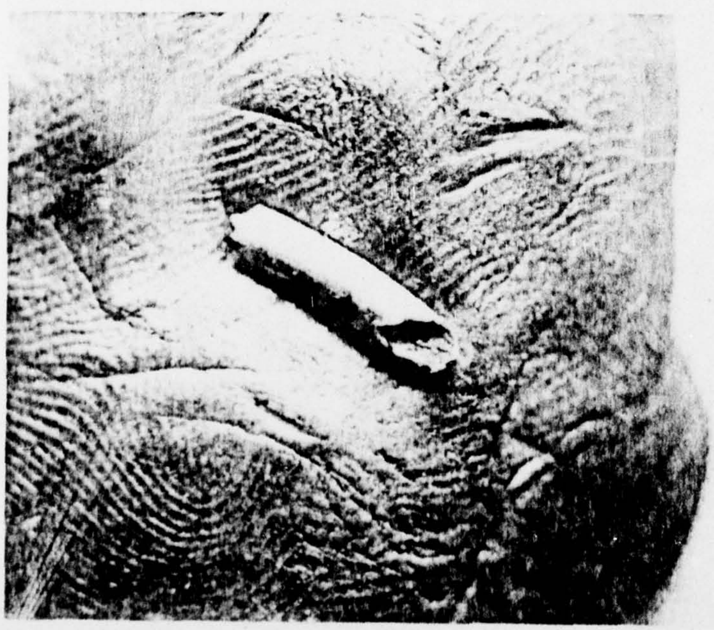


(50x)

FIGURE 21

Horizontal cracks found in FDR failed cable wire fractures when "white martensite" was involved.

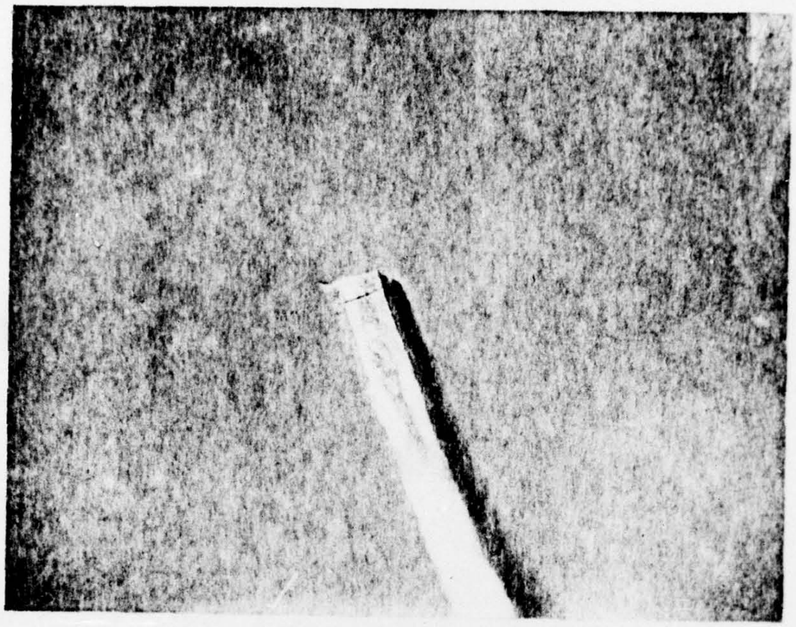
(2x)



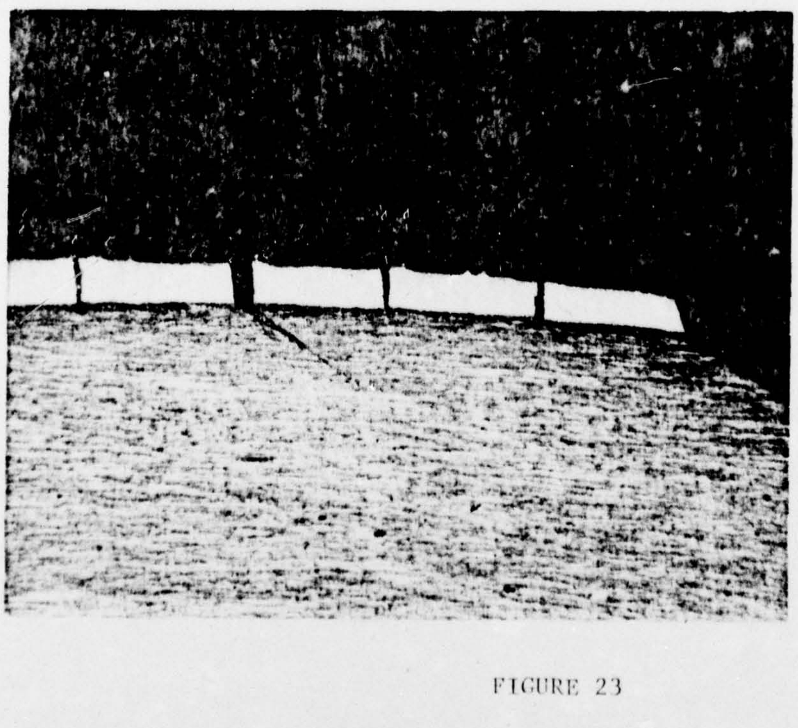
(2x)

FIGURE 22

Severe notching found on TK #1 test cable which failed on first arrestment.



(2.5x)



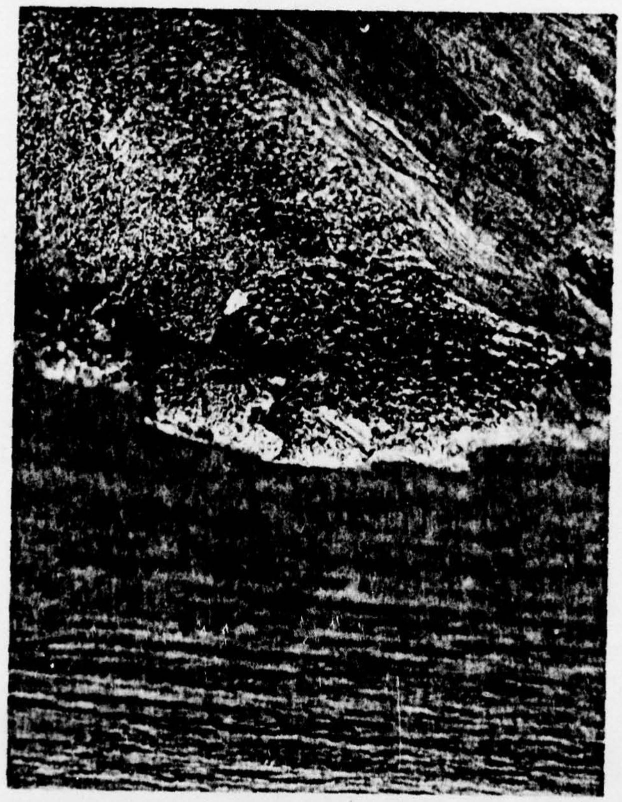
(50x)

FIGURE 23

Martensitic-type smear induced fractures found on some RALS site test cables.

FIGURE 24

View of damaged area along the toe of the hookpoint involved with the FDR Cross Deck Pendant failure.



(3x)

NOTE wire mark on base metal.

FIGURE 25

Close-up view of damaged area in Figure 24.

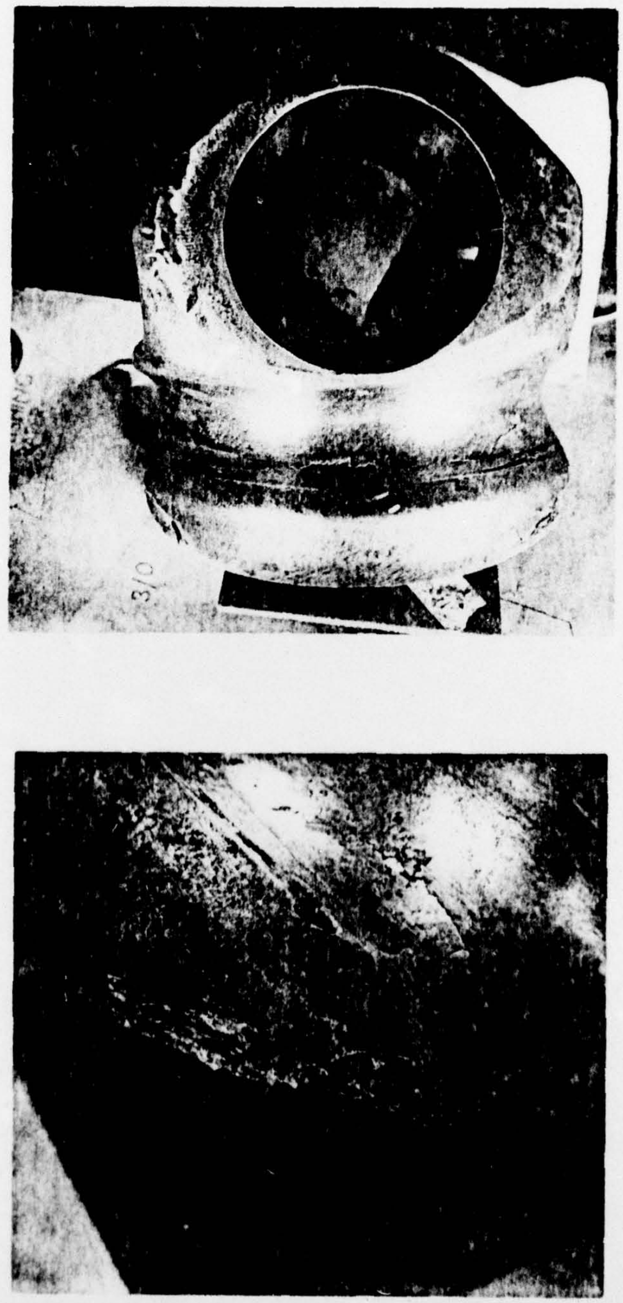


FIGURE 26

Overall view (above) and closeup of Damage sustained by hook point (Serial #9550)

XIII. APPENDIX

IMPACT BEND TEST

DESCRIPTION OF TEST APPARATUS

The Gardner heavy-duty impact tester (Model No. 1G-1120) was utilized. This unit consists of a graduated vertical tube which guides a 4 pound weight, dropped against a punch-hammer, from a maximum height of 40 inches. This enables the available impact force to range from 0 to 160 inch-pounds. (See Figure 27)

DESCRIPTION OF TEST

Before performing the actual test on various wire sample, the procedure criteria had to be established to eliminate uninformative testing and to preserve the limited number of test specimens available. This was accomplished by utilizing unimportant wire samples in a "pretest."

In this test, one operator would position the wire sample between the punch-hammer and the die. The second operator would raise the weight a desired amount and impact the wire.

The position of the "white martensite" relative to the punch-hammer was varied in steps to establish the effect of position on impact force needed to completely part a wire.

The "pretest" showed that when "white martensite" was facing the punch-hammer (face up) no amount of impact force (up to 160 inch-pounds) would break the wire test sample. In this position the "white martensite" under impact is actually in compression, not tension.

As the wire was rotated (moving the position of the "white martensite" away from the punch hammer) the impact force required to break the wire decreased. In fact, when the "white martensite" was in maximum tension (fully face down), the minimum amount of force needed to completely part a wire was established. This test also showed that the actual amount of "white martensite" was unimportant. Wires (from the same cable) with various degrees of martensite produced the same results.

The actual test utilized at least 40 wire specimens with approximately the same amount of "white martensite"from each major test cable. The NATF (RALS site) test cables and the FDR failed cable (with 22 arrestments) were tested to gain additional information, wires without "white martensite" were tested also.

The wire specimans were placed between the .500 inch punch-hammer and the .640 inch die with the "white martensite" fully face down (see figure 28). Each set of specimans were impacted from 160 inch-pounds down in increments of 20 inch-pounds. The lowest force required to consistantly part a wire is refered to as the wire's minimum impact strength. These values are listed in Table V.

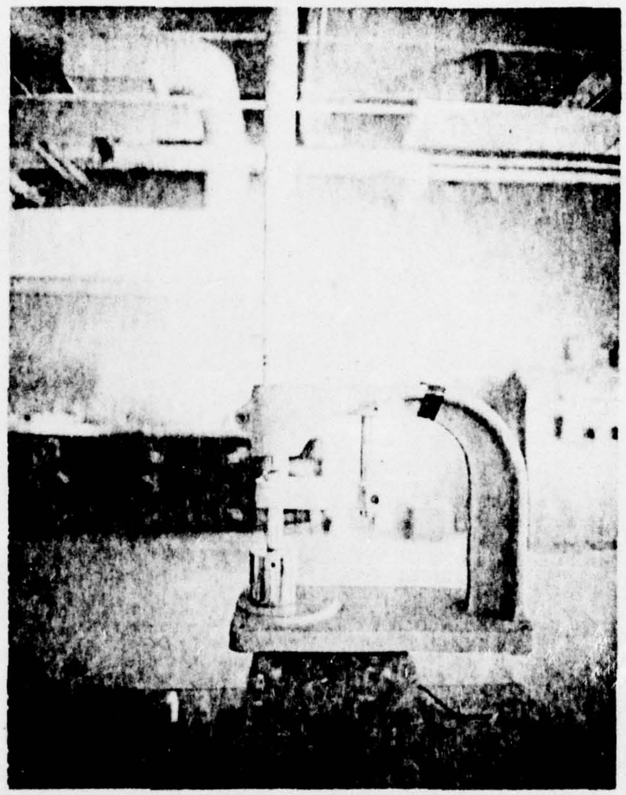
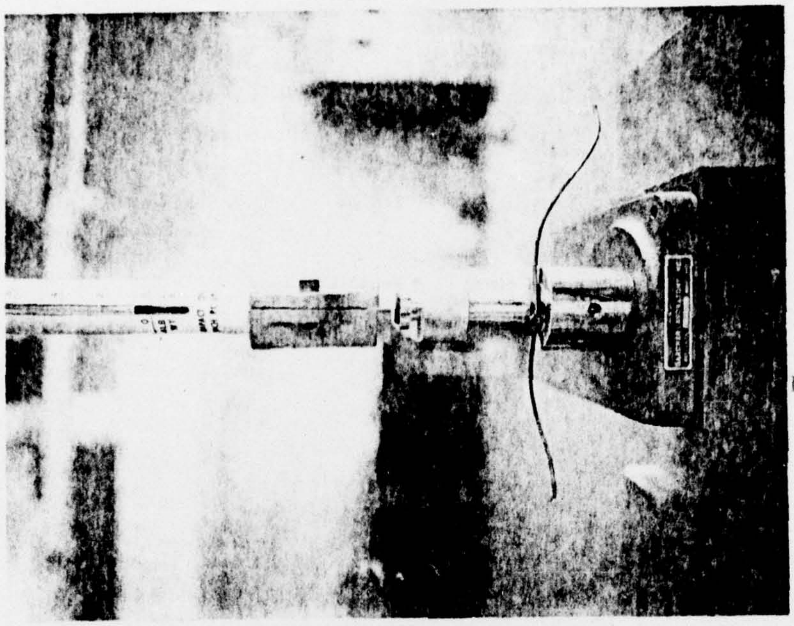


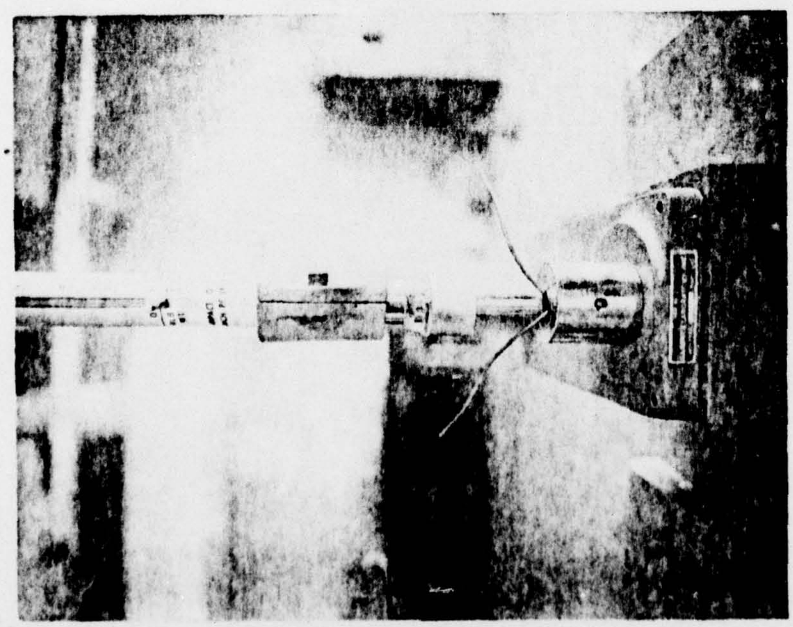
FIGURE 27

Side view of the Gardner heavy-duty impact tester



(1/2x)

Before impact test



(1/2x)

After impacting with 4-pound weight

FIGURE 28.

Position of Wire Test Specimens.

METALLURGICAL ANALYSIS OF ARRESTING GEAR DECK PENDANT FAILURES

NAEC-ENG 7910

A metallurgical investigation was made of the cross-deck pendant which failed during an F-4 arrestment aboard the CV-42. The investigation was backed with simulation test samples. Various types of wire fracture modes were identified.

METALLURGICAL ANALYSIS OF ARRESTING GEAR DECK PENDANT FAILURES

NAEC-ENG 7910

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